MOLECULAR GAS IN THE SPECTACULAR RING GALAXY NGC 1144

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ABSTRACT

We have detected extremely wide (1100 km s^{-1}) CO(1–0) emission from NGC 1144, an interacting, luminous infrared galaxy that is the dominant component of the Arp 118 system. The observations show that NGC 1144 is one of the most CO luminous galaxies in the local universe, with a CO luminosity twice that of Arp 220. Maps with the IRAM interferometer show that the CO is not in or very near the Seyfert 2 nucleus, but in the 20 kpc diameter ring that extends halfway between NGC 1144 and the elliptical galaxy NGC 1143. The greatest gas concentration, with 40% of the CO luminosity, is in the southern part of the ring, in NGC 1144. Another 15% of the CO luminosity comes from the dominant 10 μm source, a giant extranuclear HII region. The ring of molecular gas, the off-center nucleus, the ring extending halfway to the intruder, and the velocity of the intruder nearly equal to the escape velocity all show that Arp 118 is a ring galaxy produced by a collision of a massive spiral with an elliptical. The most spectacular property is the velocity range, which in Arp 118 is 2 to 3 times higher than in a typical ring galaxy. Arp 118 is a rare example of a very luminous extended starburst with a scale of about 5–10 kpc, and a luminosity of 3 $\times$ 10^{11}L$_\odot$.

Subject headings: Galaxies: individual (Arp 118, NGC 1144, NGC 1143) – galaxies: interactions – galaxies: starburst – galaxies: ISM – infrared: galaxies – ISM: molecules

1. INTRODUCTION

Most luminous infrared galaxies are merging or interacting with strong nuclear concentrations of molecular gas. There is, however, another class of interacting galaxies, ring galaxies with non-nuclear but coherent starbursts. The Arp 118 system has long been recognized as a member of this class (e.g., Freeman & de Vaucouleurs 1974). Its IR luminosity [2] , $L_{\rm IR} = 2.5 \times 10^{11}$ $L_\odot$, is one of the highest, about 10 times that of other ring galaxies (Appleton & Struck-Marcell 1987). The Arp 118 pair consists of a disk galaxy, NGC 1144, that has interacted with NGC 1143, an elliptical galaxy $40''$ northwest (Fig. 1). NGC 1144 has a strongly distorted disk, two bright optical sources in its central regions, a stellar bridge seen at $2\,\mu$m between the two galaxies (Joy & Ghigo 1988 [JG88]), and a ring of HII regions extending halfway between NGC 1144 and NGC 1143 (Hippelein 1989 [H89]).

Arp 118's morphology and velocity spread indicate a strong interaction. Although the systemic velocities of the nuclei of NGC 1144 and NGC 1143 differ by only $300\,{\rm km\,s^{-1}}$, the internal velocity spread in NGC 1144 is much higher. Observations of $\mathrm{H}\alpha + $[NII] and other lines show velocity shifts over $1100\,{\rm km\,s^{-1}}$ (H89). The strongest starburst is a giant HII region complex $8''$ west of the nucleus. This giant HII region dominates the galaxy's $10\,\mu$m and Hα luminosities even though NGC 1144 has a Seyfert 2 nucleus (H89; Osterbrock & Martel 1993). There are several non-thermal radio sources in NGC 1144, including a very compact radio source at the nucleus, and a strong extended region $5''$ to the northeast (JG88; Condon et al. 1990; Fig. 1).

In contrast to the higher-energy activity traced by the relativistic particles and the ionized gas, the far IR colors indicate cold dust at 34 K. To see whether the cold, massive, molecular gas showed the same extreme kinematics as the ionized gas, we made molecular

[2] for $H_0 = 75$ ${\rm km\,s^{-1}\,Mpc^{-1}}$, the distance to Arp 118 is 118 Mpc.

line observations with the IRAM 30 m telescope and the IRAM interferometer.

2. OBSERVATIONS AND DISTRIBUTION OF THE MOLECULAR GAS

CO observations were made with the IRAM 30m telescope on Pico Veleta near Granada, Spain. We used 512 × 1 MHz filterbanks and SIS receivers with SSB system temperatures of 250 and 450 K ($T_{\rm a}^*$), respectively, for CO(1–0) and CO(2–1). Both lines were observed simultaneously. Pointing was checked by observing nearby quasars every two hours, with errors $\sim 3''$. We also looked for HCN(1–0) and CS(3–2), with system temperatures of 270 and 300 K, respectively. The beamwidths were $23''$ and $28''$ for CO(1–0) and HCN(1–0). CO was observed at three positions in Arp 118 (Fig. 1) and HCN was observed only toward NGC 1144. Integration times were 30 to 60 min for each position in CO and 4 hours in HCN. The 500 MHz spectrometer bandwidth barely covered the very wide lines in CO(1–0), and CO(2–1) was used only to confirm detections.

CO(1–0) was also observed with the four 15m antennas of the IRAM Interferometer on Plateau de Bure, France. Three configurations gave a synthesized beam of $5.3'' \times 2.5''$ at position angle (p.a.) 20°. The SIS receivers had SSB system temperatures of 300 K. The spectral coverage was 480 MHz (1285 km s^{-1}) with a resolution of 2.5 MHz (6.7 km s^{-1}). Since the interferometer's field of view is $45''$ (FWHM) at 3 mm, we mapped Arp 118 with two overlapping fields. The first field covered NGC 1144 and the second covered the northwest part of the ring and NGC 1143.

The single-dish CO line profile in NGC 1144 is remarkably strong and wide, $\sim$ 1100 km s^{-1} to zero intensity (Fig. 1). This is the widest CO line ever detected. CO was also detected in the northwest part of the ring, at $17''$ (10 kpc) from the main disk of NGC 1144. At this position, the single-dish CO spectrum peaks at $\sim$ 8250 km s^{-1} (Fig. 1). No CO was

detected in the elliptical NGC 1143. Weak HCN(1–0) (not shown here) was marginally detected in NGC 1144 at 9100 km s^{-1}The implied HCN-to-CO intensity ratio in NGC 1144 is comparable to that of normal spiral galaxies (Solomon et al. 1992). CS(3–2) was not detected.

The CO emission near 9100 km s^{-1} in the single-dish spectrum of NGC 1144 (Fig. 1) corresponds to the strong CO sources 6 and 7 detected by the interferometer in the south of the ring (Figs. 2 and 3). The emission near 8700 km s^{-1} corresponds to the CO sources 1, 2, and 3 in the giant H II complex west of the nucleus, and to CO source 9 in the north of the ring. The peak CO flux in these features is 80 – 150 mJy, which corresponds to a beam averaged brightness temperature $T_{\rm b} \sim 1\,{\rm K}$. In the interferometer map, the sources in the ring account for 85% of the CO flux seen with 30 m telescope.

The 30 m spectrum of northwest part of ring (Fig. 1) peaks at 8250 km s^{-1}, and arises in CO sources 12 and 13 on the interferometer map (Fig. 3). The flux detected by the interferometer from these two CO sources is 65% of the flux in the 30 m beam at the northwest ring. This may be due to these sources being near the half power point of the primary beam of the interferometer, for which no correction was made. The high velocity tail in the 30 m spectrum at the northwest part of the ring (Fig. 1) is probably emission from NGC 1144 in the skirts of the beam.

The interferometer maps show the CO is neither at the Seyfert nucleus, nor in the central disk of NGC 1144, but rather in the north, south, and northwest parts of the ring, and the giant HII complex west of the nucleus (Figs. 2 and 3). The main CO sources are at projected radii of 3 to 6 kpc ($5''$ to $10''$) from the nucleus. Except at the nucleus, the velocity and spatial distributions of the CO (Fig. 2) both agree with those of the ionized gas (H89).

Table 2 lists the CO sources on the interferometer channel maps (Fig. 2). Most of the

CO luminosity comes from the strong CO sources 5 to 8, in the south part of the ring, at $v = +260$ and $+400$ km s^{-1}, relative to $cz_{\rm lsr} = 8750$ km s^{-1}(the heliocentric velocity is higher by 12 km s^{-1}). Other prominent molecular features in the channel maps at -160 and -20 km s^{-1} are the CO sources 1, 2, and 3 (Fig. 3) in the giant HII region west of the nucleus. These CO sources are embedded in the 3 kpc total extent of the giant HII complex, which dominates the 10 μm and Hα emission (JG88; H89). It has an Hα luminosity of 7×10^{40} erg s^{-1}, five times more than the nucleus and 10 times brighter than 30 Doradus. There is no CO peak at the strong, extended radio source 5″ (3 kpc) northeast of the nucleus, which is also weak in Hα. The radio continuum may come from supernova remnants in a region with low molecular gas density.

3. NGC 1144 AS A RING GALAXY

NGC 1144 is an excellent example of a ring galaxy, with an elongated ring drawn out over a 20 kpc diameter toward the elliptical NGC 1143. Ring galaxies result from low-speed, collisions of compact galaxies with gas-rich disks (Lynds & Toomre 1976; Theys & Spiegel 1976; Toomre 1978). The impact parameter must be within 15% of the target's outer radius. The passage is roughly along the minor axis of the disk, but need not be pole-on; impacts tilted as much as 45° from pole-on yield rings. An intruder approaching in the sense of the target's spin generates a well-defined ring. An approach in the retrograde sense yields a messy ring (Lynds & Toomre 1976).

The Arp 118 system differs from other ring galaxies in several respects. The most spectacular difference is the 1100 km s^{-1} velocity range, which is 2 to 3 times higher than in all other known ring galaxies. Second, its CO emission is unusually strong. Most ring galaxies have CO luminosities ten times lower than Arp 118 (Horellou et al. 1995). Third, its ring is a splattered mess with many overlapping shock waves, rather than a smooth,

sharp ellipse like the galaxy II Hz 4 (Lynds & Toomre 1976) or the Cartwheel galaxy (e.g. Fosbury & Hawarden 1977; Higdon 1995, 1996). This suggests the elliptical passed in the retrograde sense relative to the spiral's spin. Fourth, more than in most rings, the nucleus of NGC 1144 is well off-center, with a projected radius of only 3 kpc to the southern and eastern CO sources, but with radii $\gtrsim$15 kpc to the CO and Hα sources in the northwest part of the ring. This implies the elliptical has a significant fraction of the system's mass and has pushed the nucleus of the spiral off center. A good analogy to the position of the nucleus and the commotion in the Arp 118 ring is the retrograde model in the middle of Fig. 6 of Lynds & Toomre (1976). While other interpretations are possible, including a model involving the interaction of 2 or more spirals now observed as parts of NGC1144, the high velocities can best be reproduced in a "ring" galaxy encounter.

4. INTERPRETATION OF THE KINEMATICS

To account for the high velocities and the Hα ring morphology Hippelein (1989) made an 3-body model of a nearly face-on collision between a spiral and an elliptical. His data show an apparent sine-wave pattern in the Hα velocity vs. p.a. (position angle) in the ring, with an amplitude of 510 km s^{-1}, which is confirmed by our CO observations. By assuming the ring was circular, and inclined to us by 50° along a major axis at p.a. 127°, Hippelein derived a rotational velocity of 670 km s^{-1}, which he noted would imply an unrealistically high dynamical mass $> 10^{12}$ M$_\odot$. We suggest here an alternative to Hippelein's model that differs from his in the time scale and repartition of rotational and radial motions.

In our interpretation, the disk galaxy was originally a massive, gas-rich spiral. Scaling the stellar mass derived from the K-band flux (JG89) to our adopted distance, we estimate a mass, in M$_\odot$, of

$$M(< R) = 3 \times 10^{10}\ R_{\rm kpc} \quad . \tag{1}$$

The K-band flux indicates the elliptical has half this mass (JG89). The rotation velocity corresponding to the spiral's mass is $350\,\mathrm{km\,s^{-1}}$. If, as in Hippelein's model, the elliptical traversed the disk at a radius of 2 kpc, it acquired a velocity of $V_{\rm esc} = \sqrt{2}V_{\rm rot}$, or $490\,\mathrm{km\,s^{-1}}$. Relative to NGC 1144, the elliptical now moves toward us with its velocity vector at 30° to 45° to our line of sight, so we see a a line of sight component of $\sim 340\,\mathrm{km\,s^{-1}}$. The elliptical is at a projected distance of 22 kpc from the disk galaxy, with a true distance of 29 kpc. The center of mass of the pair of galaxies is two-thirds the way from the elliptical to the spiral, or 19 kpc, so closest approach occured 40 Myr ago.

The encounter has drawn out some of the stars and gas in the former disk of NGC 1144 in an ellipse (R-band image in Fig. 1). The northwest part of the ring approaches us, the part of the ring south of the nucleus recedes. Since the elliptical heads at us, we look down the long axis of the ellipse. In ring galaxies, the encounter provokes a density wave that rapidly rebounds outward at half the intruder's velocity, i.e., at $V_{\rm rot}/\sqrt{2}$, or $250\,\mathrm{km\,s^{-1}}$ for Arp 118. This is consistent with the ring extending half the distance to the elliptical. The ring expansion and rotation yields an apparent line of nodes at p.a. 130° east of north on the sky (H89). As in other ring galaxies, however, the minor axis must be roughly in the direction from the spiral to the elliptical, that is, east-west. Hence the original disk must have been nearly edge-on to our line of sight, with the true line of nodes nearly north-south.

We have compared the observed CO and $H\alpha$ kinematics with a model combining rotation and expansion. We get a reasonable fit with a disk kinematic major axis at p.a. $-10°$ and the original disk plane inclined 20° to our line of sight. The north side approaches, the south recedes. The near side is west, the far side is east. The velocity shifts north and south are the rotation component, $350\,\mathrm{km\,s^{-1}}$. The molecular clouds have the $250\,\mathrm{km\,s^{-1}}$expansion component superposed on their former rotational component of $350\,\mathrm{km\,s^{-1}}$. Because of the nearly edge-on inclination of the former disk galaxy and

the direction of the motion of the intruder (probably within 45° of our line of sight), we see the maximum combined effect of the expansion and rotational components of the elliptical-shaped ring that is pointing nearly at us. For example, CO cloud 12 was originally in pure rotation at 300 to 350 $\mathrm{km\,s^{-1}}$. After the passage of NGC 1143, it was drawn out into the farthest part of the ring, following the intruder at half its speed. Since the intruder is moving straight toward us, the cloud's streaming component of $-250\,\mathrm{km\,s^{-1}}$ adds vectorially to the former motion of $-350\,\mathrm{km\,s^{-1}}$ yielding about $-510\,\mathrm{km\,s^{-1}}$. This simple model can approximately account for the extreme linewidth by the vector addition of the rotation, expansion and a turbulent component of about 100–150 $\mathrm{km\,s^{-1}}$.

In reality, the former smoothly rotating disk of NGC 1144 no longer exists and the orbits of the gas near the nucleus are probably highly eccentric, more like bar streaming than circular rotation. The molecular clouds near the nucleus are moving along elliptical streamlines, with velocities of closest approach much higher than the circular velocity, of the order of $\sqrt{2}V_{\rm rot}$, or 490 $\mathrm{km\,s^{-1}}$. This value is close to the red-shifted velocities of CO clouds 7 and 8, south of the nucleus.

5. GAS MASS AND IR LUMINOSITY

NGC 1144 has a very high CO luminosity, mainly as a result of its large velocity spread. We think the ratio of H_2 mass to CO luminosity throughout the ring is lower than in the Milky Way molecular clouds because the extreme velocity dispersion makes the CO over-luminous. For a mean ring radius of 6 kpc, eq.(1) would imply an enclosed dynamical mass of $\sim 2 \times 10^{11}\,\mathrm{M_\odot}$. If the gas mass is 10% of the dynamical mass, or $\sim 2 \times 10^{10}\,\mathrm{M_\odot}$, then the H_2 mass to CO luminosity ratio would be two to three times lower than in Milky Way molecular clouds. The global $L_{\rm IR}/M({\rm H_2})$ ratio would be about $10\,\mathrm{L_\odot/M_\odot}$, a modest rate of star formation, but obviously unusual because of its simultaneous activity over a

very large ring.

Arp 118 probably differs from other ring galaxies in being more gas-rich and massive, and hence having a faster expansion velocity than other rings. While its ring diameter is close to the median size for the 26 ring galaxies in the sample by Appleton and Struck-Marcel (1987), its higher expansion velocity means that it is younger than most of the other known ring galaxies. Its snowplow and shock effects will also be stronger, for the same reason, which may explain why its star formation rate and consequent luminosity is nearly an order of magnitude higher than for other rings. The encounter with the elliptical has produced a series of shock waves and an immense assembly of giant molecular cloud complexes and starburst regions in a ring in the former massive, gas-rich spiral. Eventually the shock strength will diminish and the massive stars will disperse the molecular clouds. But for the time being, we are apparently seeing Arp 118 near the peak of its star forming activity.

We thank the IRAM staff at Plateau de Bure and Pico Veleta for help with the observations, and J. Condon for his radio continuum maps.

Table 1. Molecular Gas in Arp 118: 30m Telescope

Parameter	NGC 1144	NW ring	NGC 1143
α_{1950}	$02^{\rm h}52^{\rm m}38^{\rm s}.4$	$02^{\rm h}52^{\rm m}37^{\rm s}.3$	$02^{\rm h}52^{\rm m}36^{\rm s}.2$
δ_{1950}	$-00°23'09''$	$-00°22'55''$	$-00°22'47''$
mean $cz_{\rm CO}$ (km s^{-1})	8810	8507	
median $cz_{\rm CO}$ (km s^{-1})	8750	—	—
$\Delta V_{\rm CO}$(FWHM) (km s^{-1})	657	~ 450	—
$\Delta V_{\rm CO}$(FWZI) (km s^{-1})	1120	750 – 1100	—
$I_{\rm CO}$ (K km s^{-1})[a]	36.0	10.2	≤ 1.0 (2.5σ)
$L_{\rm CO}$ (K km s^{-1} pc^2)	8×10^9	2×10^9	$\leq 2 \times 10^8$
$I_{\rm HCN}$ (K km s^{-1})[a]	0.7 ± 0.2	—	—
$L_{\rm IR}$ ($L_\odot$)	3×10^{11}	—	—
$L_{\rm B}$ ($L_\odot$)	5×10^{10}	—	9×10^{10}
D (Mpc)	118	—	—

[a]$T_{\rm mb}$ scale for IRAM 30m telescope; at 3 mm, $S/T_{\rm mb} = 4.7$ Jy K^{-1} for a point source.

Table 2. CO Sources in NGC 1144 (Arp 118): IRAM Interferometer

CO Source and location	$\Delta\alpha, \delta$ [a] (arcsec)	V [b] ($\mathrm{km\,s^{-1}}$)	S_{CO} [c] (mJy)	Radius [d] (kpc)
1 west	−6 , −1	20	90	3.5
2 west	−8 , −3	−80	90	4.6
3 west	−10 , −2	−180	80	5.6
4 south	−7 , −7	200 ?	50	7.3
5 south	−2 , −8	300	120	4.7
6 south	2 , −5	380	170	3.0
7 south	5 , −2	420	120	3.1
8 south	6 , −1	460	80	3.5
9 north	2 , 8	−120	120	4.0
10 north	−1 , 10	−150	70 ?	5.8
11 north	4 ,10	360	75	6.7
12 NW	−10 , 18	−510	80	11.2
13 NW	−19 , 19	−510	50	14.5

[a] Relative to the nucleus at $02^{\mathrm{h}}52^{\mathrm{m}}38^{\mathrm{s}}.7$, $-00^{\circ}23'07.8''$ (1950) = $02^{\mathrm{h}}55^{\mathrm{m}}12.^{\mathrm{s}}.2$, $-00^{\circ}11'00.6''$ (2000).

[b] Relative to $cz_{\mathrm{lsr}} = 8750\,\mathrm{km\,s^{-1}}$.

[c] Peak flux in individual channel maps of width 40 $\mathrm{km\,s^{-1}}$.

[d] Projected distance from the nucleus.

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Fig. 1.— (Plate 1). *Left panel:* Images of Arp 118 in R band (top), Hα + [NII] after continuum subtraction (middle, Hippelein 1989), and in 1.49 GHz radio continuum (bottom, Condon et al. 1990) on the same scale. *Right panel:* The CO(1–0) spectra from the IRAM 30 m telescope at the three positions marked on the Hα image by circles indicating the 23$''$ beam. Note the wide CO lines in NGC 1144 and the northwest part of the ring. The CO(2–1) spectrum of NGC 1143 (dashed line) shows possible weak emission centered on 8350 km s^{-1}. Coordinates are (1950).

Fig. 2.— Interferometer channel maps of CO(1-0) from Arp 118 at a resolution of 140 km s^{-1}. The contour step is 14 mJy beam^{-1} (dashed contours are negative; zero contour omitted); beam = 5.$''$3 $\times$ 2.$''$5, with T_b/S = 6.7 K/Jy. Velocities are relative to $cz_{\rm lsr}$ = 8750 km s^{-1}. The cross marks the nucleus at 02$^{\rm h}$55$^{\rm m}$12.2$^{\rm s}$.7, $-00°11'00.6''$ (2000). Tick marks are 0.$^{\rm s}$5 in R.A., and 10$''$ in Dec.

Fig. 3.— (Plate 2). Interferometer map of integrated CO(1–0) contours superposed on an Hα + [NII] image of Arp 118 (Hippelein 1989). EGHR = extragalactic giant HII region. Coordintes are (1950). The CO map is integrated over 1285 km s^{-1} centered on $cz_{\rm lsr}$ =8750 km s^{-1}. The contour step is 3.9 Jy km s^{-1} beam^{-1}, with T_b/S = 7.5 K/Jy. The cross indicates the position of the Seyfert 2 nucleus. Labels indicate the CO sources referred to in the text and in Table 2 . The 5.3$''$ $\times$ 2.5$''$ beam is shown at lower left.

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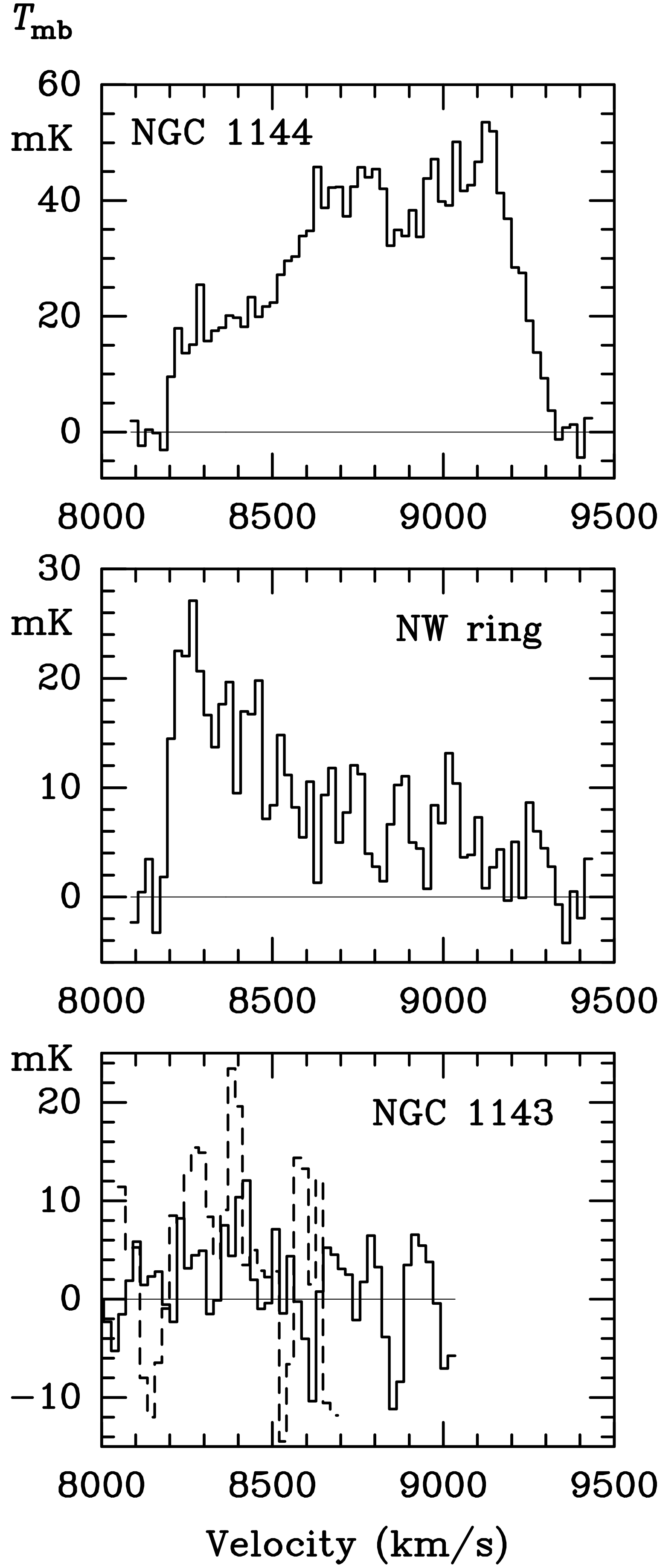
T_{mb}
mK
NGC 1144
60
40
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8000
8500
9000
9500
NW ring
30
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10
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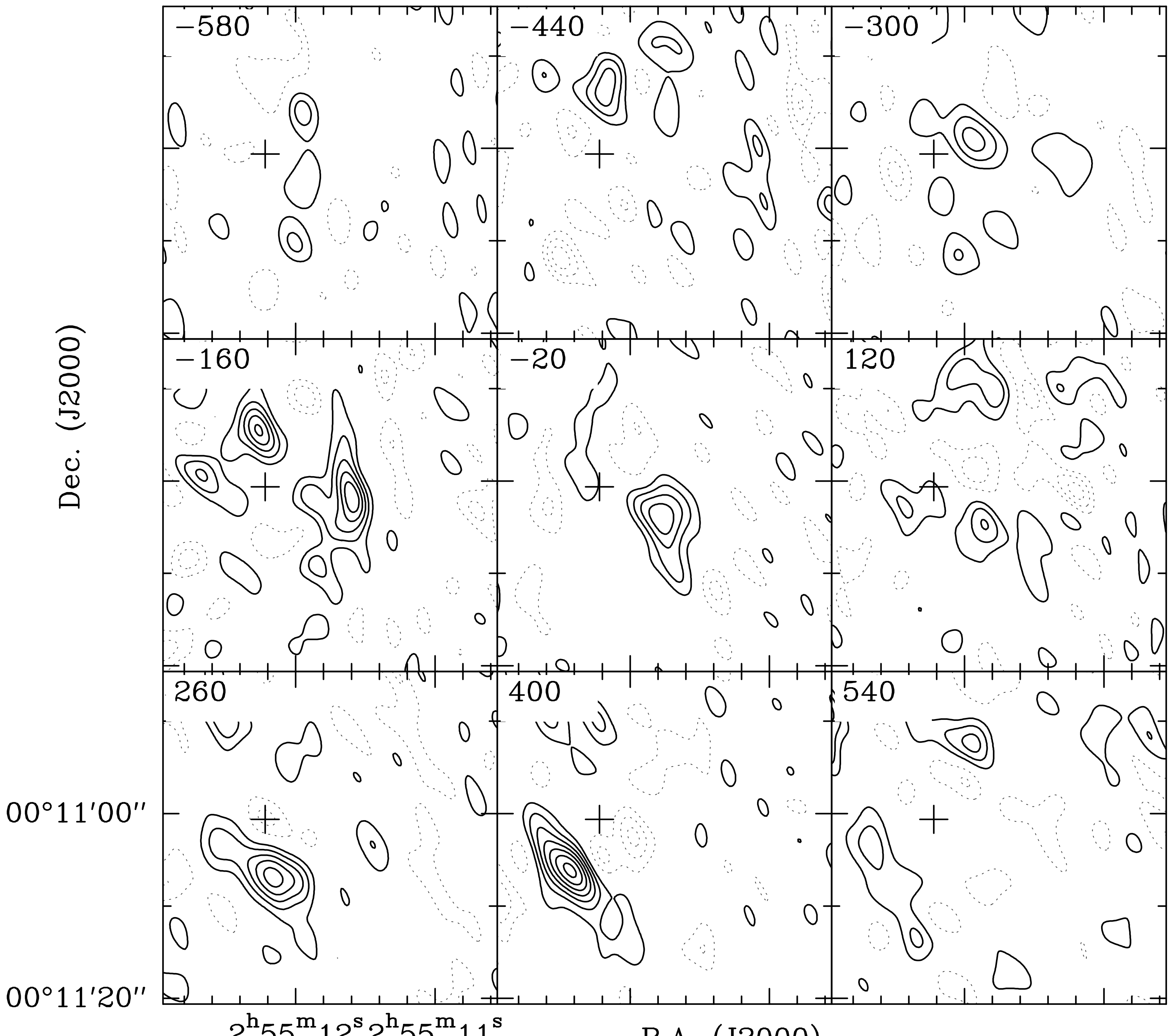
NGC 1143
−10
Velocity (km/s)



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